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Simulation, fabrication and characterization of robust vibrational energy harvester

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Abstract

A new concept for the realization of cheap and robust energy harvester which converts mechanical vibrational energy into useful electrical energy using flexible PDMS pillars and a SiO_2-electret is presented. Soft PDMS pillars are used as springs connecting a fixed and a movable electrode. Structuring of PDMS is done by punching, thus avoiding any micro structuring technique whereas in an earlier work structuring of PDMS was done via photolithography and finally RIE etching of a hard mask. The fixed electrode is oxidized with thermal wet oxidation technique to form a 0.25 µm thick electret and the electret is charged up to -260 V. Pre-treatment by plasma activation was used to increase the bond strength of PDMS. A new concept for power switching has been developed using flyback converter and thus detecting the phases of harvesting and extracting energy at proper phase in the cycle created by arbitrary motion. By this concept we are able to harvest 0.23 nW power at 1g vibration and 4.3MΩ load resistance. However, by scaling the size of the PDMS pillars from mm to µm using micromachining and by design changes which allow to harvest out of more than one direction of vibration, output power can be scaled from nW to mW.

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Keywords: Eelectrostatic energy harvester, electret, PDMS as spring, vibrational generator, Synchronous charge extraction, Simulink model.

1. Introduction

Autonomous systems, sensor networks or systems in remote areas which are difficult to access need alternative concepts other than batteries for power supply. One of the possible solutions for these applications is the use of energy harvesting in combination with a miniaturized energy storage facility.

In energy harvesting or scavenging devices energy already available in the environment is used. Typical sources of such environmental energy are vibration, thermal energy, wind, solar etc. Energy harvesters convert these types of

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energy into useful electric energy. A straightforward approach to convert vibrational energy to electric energy is capacitive transduction. First analysis of MEMS based vibrational generator based on spring mass damping system was by Williams & Yates [1] in year 1996. In principle, vibrational capacitive energy harvester work either in-plane (vibration changes overlap between electrodes) or out-of-plane (change of gap between electrodes). Out-of-plane harvesters suffer from the pull-in effects which limits the range of movement of the movable electrode and thus the energy output considerably. In order to achieve really autonomous systems, capacitive energy harvesters have to make use of so-called electrets which are able to store charge for long time. Detailed studies of electret based vibrational generator were done in [2, 3]. Commonly used electrets are CYTOP, Teflon, PTFE (Polytetrafluoroethylene), SiO_2 and Si_3N_4. Recently, Karagozler et al. [4] presented a paper generator which is an interesting design of a capacitive electrostatic energy harvesting using out-of-plane movement and PTFE as electret.

1.1. Working principle

The basic concept has been presented in [5]. Due to an external vibration *y (t)* the proof mass on the movable electrode oscillates periodically in vertical direction *x (t)* and also in horizontal direction *z (t)* depending on nature of vibration, normal or shear load respectively. As a result variable AC voltage is generated (Fig. 1). Two highly doped silicon plates act as parallel plates of a capacitor. A quasi permanent charged SiO_2 electret act as voltage supply. Charging can be efficiently done by simply using a hair dryer with ionic function [6]. Four PDMS pillars act as springs and stop thus preventing pull-in. Compared to micromechanical designs where the springs are realized typically by beam suspensions, the use of PDMS pillars provides efficient stops thus avoiding pull-in. Fig.1 (b) shows equivalent representation of energy harvester model with the vertical direction only.

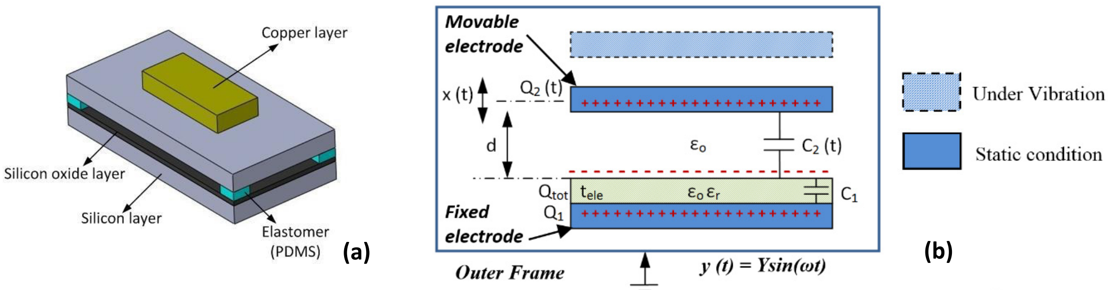

Fig. 1: (a) Schematic diagram of energy harvester [5] and (b) Electret based electrostatic generator model.

2. Simulink model of robust energy harvester

A Simulink model was developed to study the behavior of the energy harvester, forecast and optimize the energy, which can be harvested. For simulation, parameters considering experimental pre-tests and fabrication aspects (s. section 3) were (Table 1). Electrets based vibrational energy harvester can be described as spring-mass damping system and equivalent mathematical model has been simulated in MATLAB using Simulink tool. For Simulink model only normal load (1-D motion, out-of-plane) is considered. Due to external vibration $y(t) = Y\sin(\omega t)$,

Table 1. Optimized parameters used for Simulink model of robust energy harvester.

Parameters	Values	Parameters	Values
PDMS thickness	60 µm	Resonance frequency (f_c)	828 Hz
PDMS area	$1.26{*}10^{-5}$ m^2	Quality factor	4.76
Total mass (m)	6 gram	Damping coefficient (b_m)	6.7 Ns/m
Spring constant (k)	157000 N/m	Load resistance (R)	4MΩ
Damping factor (ξ)	0.1050	Critical damping co-eff (C_c)	63.69 Ns/m

proof mass undergoes relative displacement $x(t) = X\sin(\omega t+\phi)$ with respect to outer frame (Fig. 1b). Kinetic energy loss occurs due to two damping forces: First mechanical damping (b_m) (squeeze film damping in case of two parallel plate with small gap in µm) and second electrostatic attractive force (F_{ele}) between two charged plates. Based on Newton's second law spring mass damping system is represented as differential equation given (1):

$$\ddot{x} = -\ddot{y} + g - \frac{b_m}{m}\dot{x} - \frac{k}{m}x - \frac{F_{ele}}{m} \tag{1}$$

In equation (1) F_{ele} is the attraction force between two charged plates given by

$$F_{ele} = \frac{1}{2}\frac{Q_2^{\,2}(t)}{\varepsilon_o A} \quad (2) \qquad \frac{dQ_2(t)}{dt} = \frac{V_{ele}}{R} - \frac{Q_2(t)}{C(t)\times R} \quad [2]\ (3) \qquad C_2(t) = \frac{\varepsilon_o A}{d + d\times x(t)} \quad (4)$$

Equation (3) gives current generated by MEMS capacitive generator which is found by considering electrets as constant voltage source in series with MEMS capacitor and applying *Kirchhoff's voltage law* in equivalent circuit. Equation (4) gives the change in capacitance due to relative motion *x (t)* around static distance between two plates (Fig. 1 b).

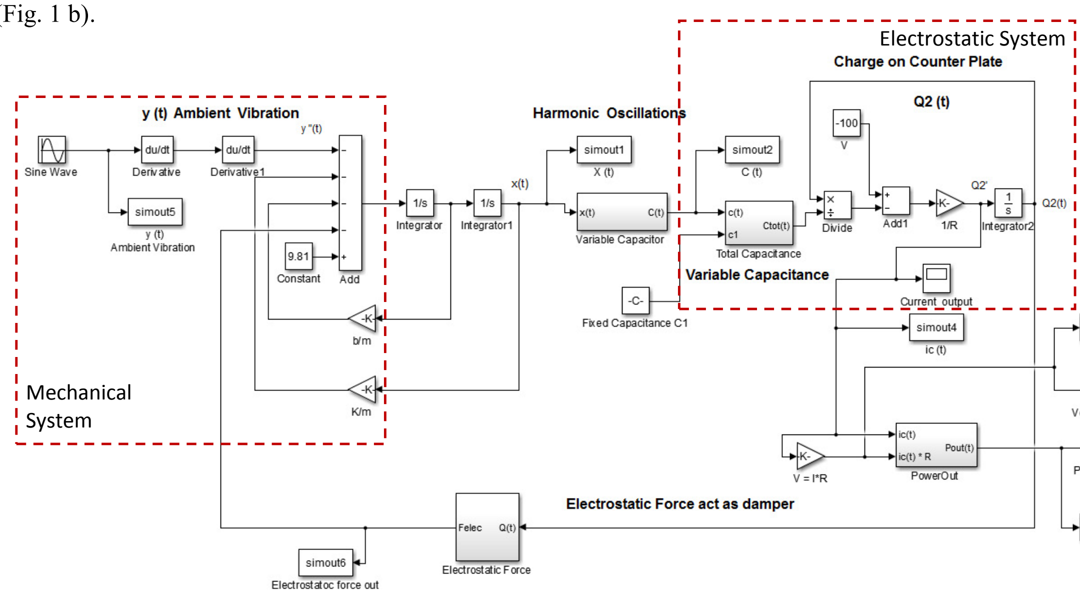

Fig. 2: Simulink model of an Electret based Vibration Energy harvester.

With this analytical Simulink model of the energy harvester as shown in (Fig. 2) we have calculated 17.8 mV voltage (rms) and 0.2 nW average power at R_L= 3MΩ and y_o = 20 µm (1g= 9.8 m/s²) vibration (Fig. 3 right). Fig. 3 left shows, that an increase of proof mass by a factor of 2 results in 1.45 times more harvested energy and reduces the resonance frequency by a factor of 1.4.

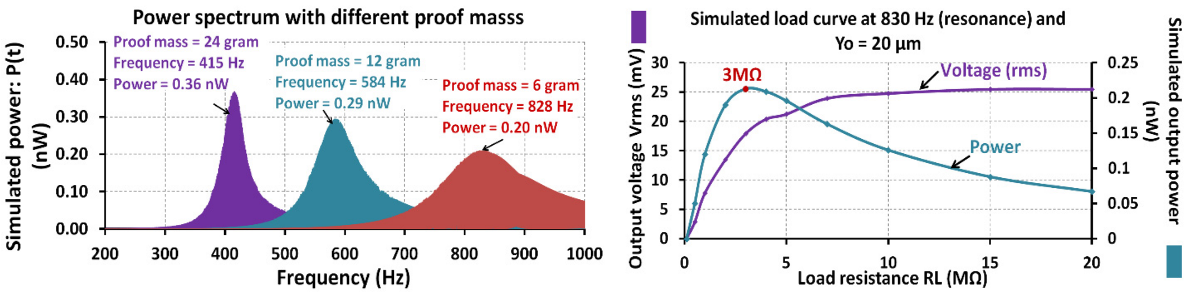

Fig. 3: Left: Output power for different proof mass. Right: Output power with different load resistances

3. Fabrication of robust energy harvester

Essential parts of robust energy harvester include 2 highly p-doped Si plates as electrodes, SiO_2 electret, PDMS pillars, Aluminium contact to extract induced charges and proof mass; the graphical representation of prototype is shown in Fig.1a. Movable electrode (2x2 cm²) and fixed electrodes (2.5x2 cm²) are highly Boron doped with aluminium on back side. The fixed electrode is oxidized with thermal wet oxidation technique to form 0.25 µm thick SiO_2 electret. Diameter of the 4 PDMS pillars is 2 mm each and thickness is 60 µm. PDMS used in this work is Sylgard® 184 Silicone Elastomer (base agent/curing agent = 10/1). After inserting base agent and curing agent (10:1) into double syringe (SULZER Ltd) with mixer (MKHX 02-12D) straight tip, degassing was done for approximately 30 min to avoid bubble formation during curing. After coating PDMS on a dummy plastic wafer (circular cut plastic foil), hard baking (curing) was done in oven at 90˚ C for 30 minutes. In order to structure PDMS pillars without micro structuring techniques, punching of PDMS was carried out with the help of punching tool with 2 mm diameter, without cutting the plastic wafer under the PDMS. Excess PDMS around PDMS pillars was pilled off using sharp tweezers (Fig. 4a top chip). Activation of PDMS pillars and movable electrode was done in a barrel reactor (O_2 plasma, Pressure: 1.6Torr, Power: 100W, Oxygen: 400sccm, Time: 30 seconds). Direct after activation, the PDMS pillars (on the plastic wafer) are transferred from the plastic chip to the movable electrode (Fig. 4a): Bonding is done in oven (90º C, time = 45 min, 2 kg weight on top). Meanwhile, the 0.25 µm thick SiO_2 electret was charged using highly efficient, low cost charging technique with ionic hairdryer as reported in [6]. A 0.25 µm thick SiO_2 electret can be charged up to approximately -250 V (breakdown voltage of SiO_2). We charged the electret for t = 30 min (3 mm distance ionic hair dryer to electret) resulting in -260 V surface potential, measured using electrostatic voltmeter (Model 541-1, TREK, USA). After activation (barrel reactor) of the movable electrode with the PDMS columns, it is bonded to the charged electret on the fixed electrode (Fig. 4b). The fixed electrode was not plasma activated, to avoid significantly reduction of charges in electret. Then the seismic mass was glued (Polytec EC 101, electrically conductive glue) on the movable electrode (curing 90˚ C, time = 45 min) as shown in Fig. 4c.

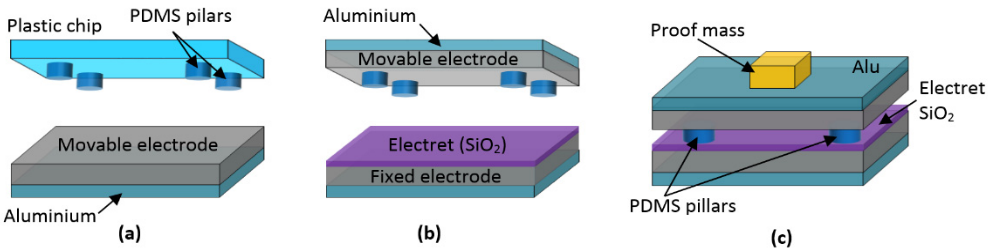

Fig. 4: Energy harvester fabrication steps (a) PDMS bonding with movable electrode and (b) Bonding movable electrode with PDMS to fixed electrode with electret and (c) Bonding proof mass on top of movable electrode.

4. Charge extraction technique

A new concept of low power switching by using a flyback converter is presented which allows a phase sensitive operation of the energy harvester (Fig. 5a). Normally, wireless sensor nodes work with DC supplies, so voltage output (AC) of energy harvester has to be converted into DC voltage in order to power up sensor node. To extract charge from capacitive energy harvester, synchronous charge extraction circuit (SCE) using full wave diode bridge rectifier and DC-DC converter (flyback converter) was reported in [7]. In this work phase detection circuit to detect positive and negative peak and generate pulse (MOSFET gate signal) has been designed. Working principle of circuit shown in Fig. 5b is that energy is only transferred from energy harvester to output capacitor when the energy harvester output reaches maximum (peak detection). At the detected maxima, short pulses are generated for switch by the power management circuit.

1) Output of energy harvester was given to diode bridge rectifier and RC differentiator circuit simultaneously, normally rectifier converts AC to DC and since there is no output path available (MOSFET off) it will perform full wave rectification and wait for MOSFET to turn on. Here, BAS 40 diodes are used because of their low threshold voltage (max V_F = 380mV) and low reverse leakage current (max I_R = 100nA).

2) The RC differentiator circuit differentiates input signal: Hence input signal peak will be converted into zero crossing. Values of R and C depend on input waveform frequency. Lower resistance value (in RC differentiator) will attenuate input sine wave hence around 10MΩ and 18 pF capacitor used for final application.
3) A MAX 919 comparator generates pulse based on differentiated signal. These pulses are integrated over time using RC integrator. Turn on time of final output pulse is (switching signal) which depends on integrator RC time constant.
4) Pulse generated from MAX 919 comparator and integrated pulse are provided to XOR logic which generates short final output pulse (turn on time = 10μs) is produced when one of the two inputs is higher than other.

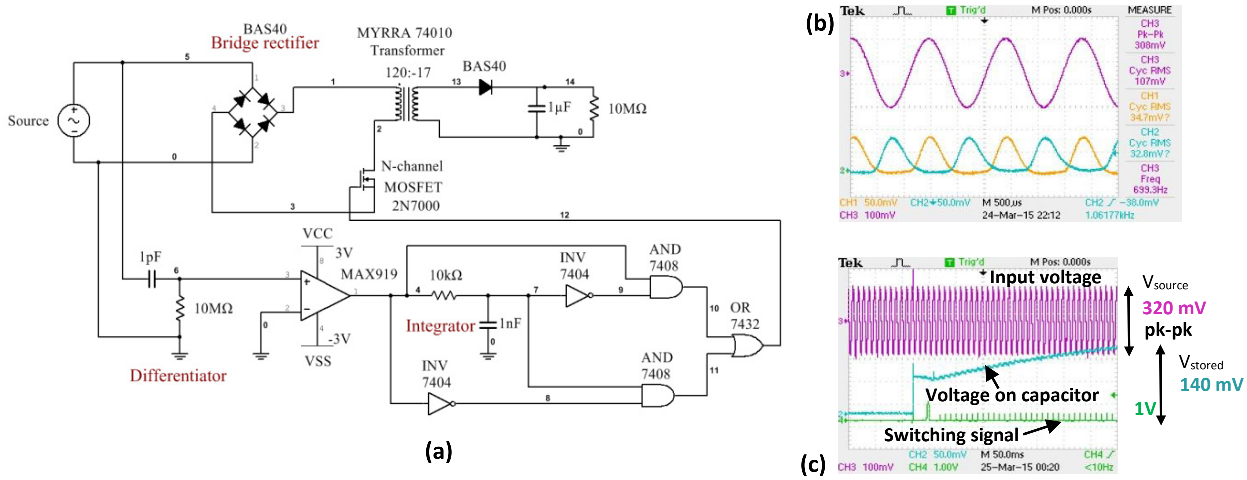

Fig. 5: (a) Circuit diagram of synchronous charge extraction technique using flyback converter, (b) Full wave bridge rectifier output with low voltage 308 mV (pk-pk)and (c) circuit operation input 320 mV (pk-pk), 100Hz given by function generator.

5. Characterization of energy harvester

After fabrication of the harvester, the prototype was characterized. The measured capacitance across the two electrodes is 50 pF which is close to the calculated capacitance of 56.9 pF. For testing, the energy harvester is mounted on PCB and is placed on a shaker (Fig. 6a). Resonance curve (Fig. 6b) and load curve (Fig. 7 right) are found using an oscilloscope (PicoScope). From resonance curve (Fig. 6b) at 1 g vibration we can derive, resonance frequency of 952.7 Hz, bandwidth of 200 Hz and quality factor of 4.75. For measurement of the load curve (Fig. 7 right), we used closed circuit with harvester, Picoscope (internal impedance 1 MΩ) and load resistor in series. At 1g vibration, optimum load resistance was found to be 4.3MΩ to harvest maximum power of 0.23 nW (Fig. 7 right). At 28g acceleration, 0.17μW output power and 414.8mV (rms) open circuit voltage has been generated (Fig. 7 left) at 909 Hz frequency. The fact, that the harvester withstands 28g acceleration, confirms the good quality of the bonding process.

6. Conclusion and discussion

As proof of concept, a capacitive, electret-based device to harvest energy from vibration has been developed. PDMS-pillars are used as springs and stops between movable electrode with proof mass and fixed electrode. Due to the hyper elastic properties of PDMS (increasing Young's Modulus under compression), pull-in effect is avoided for both, in-plane and out-of-plane movement of movable electrode under vibration. The PDMS-pillars are structured by punching, thus the fabrication does not rely on any micro structuring technique. Even though the power of the first demonstrator is too low for real application (0.23 nW at 1g), by reduction of area of pillars (feasibility of factor 16 shown), increase of voltage by thicker SiO_2-electret (factor 4-5 possible as shown in [8]), and improvement of layout (chess like structure of SiO_2-electret, thus using in-plane vibration too, factor 3) output power in the order of 0.17 μW is expected without change of proof mass m. When considering a reduced bond strength of the PDMS-pillars and thus the need of corresponding reduction of seismic mass, output power of about 0.07 µW is extrapolated in respect to Fig. 3 for the presented approach. However, to provide output power in the range of some tens of mW [5], micro structuring techniques for even smaller pillars are still required.

A flyback converter and AC-DC charge extraction technique have been developed for phase detection, low power switching and according integration of harvested energy over time. The according circuit operates at voltages of 320 mV (pp) provided by the presented energy harvester.

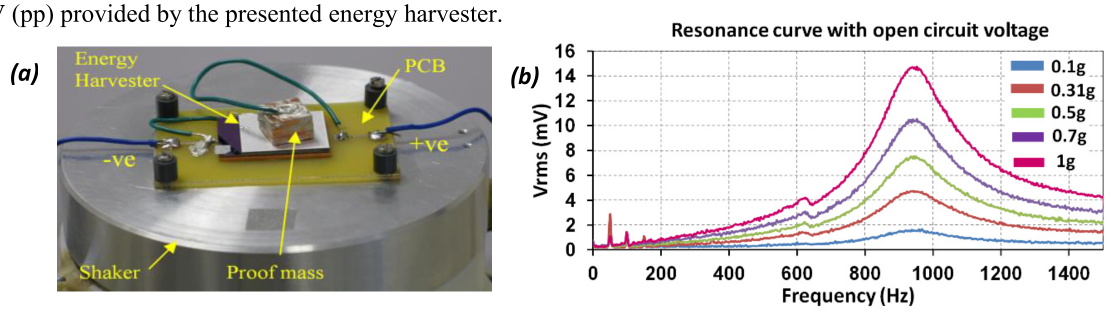

Fig. 6: (a) Robust energy harvester mounted on shaker and (b) Resonance curve after exposing the harvester to different vibration amplitudes, resonance frequency = 952.7 Hz at 1 g, $R_L = \infty\ \Omega$ (open circuit).

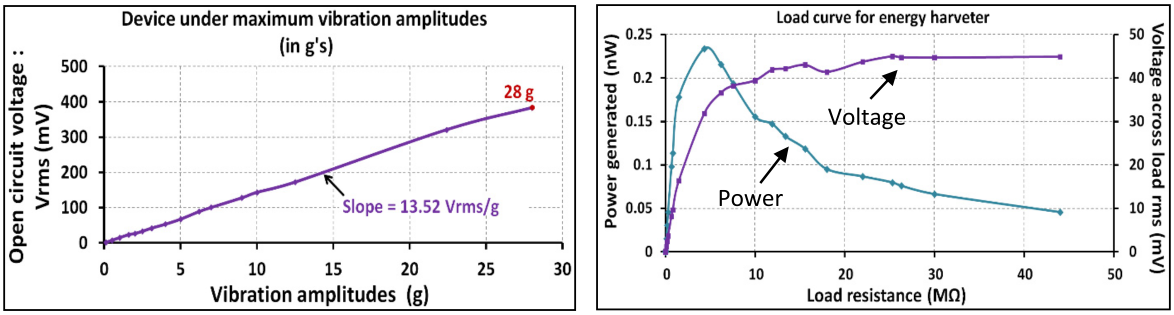

Fig. 7: Left: Acceleration dependency of open circuit voltage. Right: Load curve with different load resistance at 1g vibration and 938 Hz resonance frequency.

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